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Immersion Suit Donning in Dynamic Environments: Implications for Design, Construction & Use

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ABSTRACT: Marine abandonment immersion suits are a vital piece of safety equipment intended to protect individuals from exposure to harsh environmental elements. The operational effectiveness of a well maintained and fitted suit depends on the ability of a user to correctly don a suit system. Thirty-two participants performed immersion suit donning trials in six experimental conditions. Dynamic, pre-abandonment marine emergency scenarios were simulated using a six degrees of freedom motion platform and varying environmental lighting levels. This article details user-suit interaction challenges encountered throughout immersion suit donning tasks and examines their connection to safety and survival in marine emergencies. Analysis of user-suit functionality during the donning process is critical for identifying current deficiencies in order to develop future design solutions, training methodologies and ultimately improve users' practical competencies.

1 INTRODUCTION

Marine abandonment immersion suits are designed to provide personal protection against harsh environmental elements and the dangers of cold shock, hypothermia and drowning (Canadian General Standards Board [CGSB], 2005). In the event of an emergency, the thermal properties and functionality of an immersion suit can impact users' chances of survival (Kozey, Reilly & Brooks, 2005). The basic design and components of the "modern" era of immersion suits have remained essentially unchanged for over seventy years (Vanggard, 2007). Research conducted during World War Two identified issues critical to suit construction: lightness, simplicity, closure, flammability resistance, donning ease, effective and reliable zippers, wrist and neck seals, as well as hand protection design and configuration (Hiscock, 1980). Unfortunately, with a generally unchanged design the inherent equipment deficiencies cited in the nineteen forties are still relevant and continue to pose difficulties for manufacturers and users today.

Brooks, McCable & Lamont (2001) found overall user confidence in immersion suits was higher than what anecdotal evidence of suit performance in marine incidents suggest. The ability to maintain a suits' watertight integrity is of the utmost importance, as even small amounts of water ingress can have significant effects on the body's thermal conservation capabilities (Allan, Higgenbottam & Redman, 1985). There are three main conditions which must be met in order for a user to maximize immersion suit effectiveness: the suit must (1) be properly maintained and in good working order, (2) correctly fit the user, and (3) donned correctly (Mallam, Small & MacKinnon, 2012). The operational effectiveness of a well maintained and correctly fitted suit hinges on the ability of a user to correctly don a suit system and one must possess the knowledge and skills to do so in dynamic, real-world emergency scenarios.

2 BACKGROUND & PURPOSE

Recent research investigating immersion suit donning in dynamic environments examined the performance of donning tasks in simulated emergency scenarios (Mallam et al., 2012). The aforementioned publication examined donning timing, but also provided a platform which captured user-suit interaction throughout the donning process. Over the course of data collection, unforeseen and reoccurring issues arose which impeded successful completion of various donning tasks, prompting a lengthy quantitative analysis of task errors. The purpose of this article is to qualitatively detail immersion suit donning barriers observed during data collection by analysing specific suit components and donning procedures. Analysis of user-suit functionality throughout the donning process can advance design solutions for manufacturers and contribute to user training procedures and competencies under the constraints of current equipment. The goal is to increase awareness of potential challenges present during the pre-abandonment donning phase relating to both immersion suit donning and its connection to more general applications of safety and survival in emergencies.

3 MATERIALS & METHODS

Thirty-two novice participants (male=18, female=14; age 22.9 ± 2.0 years; stature 173.5 ± 8.6 cm; mass 75.6 ± 12.9 kg; Body Mass Index 24.9 ± 2.8) performed seven donning trials each (total trials = 224) taking place on a six degrees of freedom (6DOF) electric motion simulator (Series 6DOF2000E Electric Motion Platform, MOOG Inc., East Aurora, New York). The motion simulator was mounted with a 2m x 2m metal platform enclosed by 103cm safety railings and a 215cm canopy intended to eliminate visual references.

Participants were randomly assigned one of two marine abandonment immersion suit models, both commercially available and adhering to international regulatory standards. Both models are of similar design: traditional front entry, central split neck immersion suits sealed by one main zipper on the anterior side of the suit, detached hand protection stowed in the suits' sleeves and rubber wrist and face seals (see Figure 1). All suits used in the experiment were direct from the retailer and were new or professionally refurbished. The suits were folded and stowed in carry bags for each trial as per manufacturer instructions.

Participant anthropometric and mass measurements were collected. Standardized test clothing (basic one-piece coveralls) was provided to wear for the duration of the experiment. A specific suit size was issued based on each respective manufacturer sizing chart and participant morphological data. Participants were asked to remove potentially obstructive items such as jewellery, eyeglasses and watches, whilst long hair was tied back. A heart rate monitor was attached around the chest and a ten-minute baseline measurement was recorded to determine the length of inter-donning trial rest periods. Each rest period was unique and defined by the participants' Recovery Threshold (RT) formula as defined by Larson & Potteiger (1997) using real-time heart rate measurements. The minimum rest period length was established at five minutes, regardless of how quickly a participant reached their RT.

Figure 1. Comparison of the two immersion suit models used

Upon completion of a familiarization period with a standardized set of donning instructions participants were asked to complete seven semi-randomized donning trials in six experimental conditions (baseline condition- Condition 1- repeated twice) (see Table 1). Two lighting conditions were used with each platform condition: "Light" and "Dark". The "Light" condition was defined as normal, ambient room lighting in a windowless space, with all overhead laboratory lights activated. The "Dark" condition was defined as having all overhead and task lights deactivated, including shielding of computer monitor screens, creating a black-out environment. Three platform motion conditions were used: (1) flat motionless, (2) fifteen degree static platform list and (3) 6DOF motion replicating vessel movements in heavy seas.

Table 1. Experimental conditions

Condition	Platform Condition	Platform Condition Criteria	Visibility
1	Stable	Flat Platform, Zero Motion	High (Light)
2	List	15° Platform List, Zero Motion	High (Light)
3	Motion	6DOF: +/- 30 deg/s pitch, roll, yaw; +/- 0.5 g heave, surge sway	High (Light)
4	Stable	Flat Platform, Zero Motion	Low (Dark)
5	List	15° Platform List, Zero Motion	Low (Dark)
6	Motion	6DOF: +/- 30 deg/s pitch, roll, yaw; +/- 0.5 g heave, surge sway	Low (Dark)

Donning trials were captured via two video cameras (1 infrared, wide angle lens mounted within the motion platform; 1 standard hand held video camera mounted externally). Video data was streamed live to monitor participant progress and safety, while recordings were reviewed post-hoc to analyse participant donning procedures. Rest periods were given between each donning trial while the researchers inspected and repackaged the suit into the carry bag.

4 RESULTS & DISCUSSION

4.1 *Suit Sizing*

Ideally, everyone working on or near cold water would have access to a custom fit immersion suit specifically manufactured for individual body morphology. In reality, this is rarely feasible or practical in commercial operations. Thus, manufacturers design immersion suits for the populace using universal size ranges. Operational benefits and drawbacks exist for both custom fit and universal size suits.

The greatest advantage of a universal size immersion suit is that it *should* fit a large percentage of the adult population and thus, adequate for a range of individuals. Universal sizes facilitate and encourage smaller commercial owners and operators to purchase immersion suits knowing that they *should* fit the majority of their crew regardless of shift change or personnel turnover, keeping costs comparatively lower. In practice, during emergency muster and escape, individuals may not have the ability to access or identify a suit of specific make or size. This can become increasingly difficult with larger crew sizes, rig or vessel size/design, suit stowage areas, muster locations and a host of additional variables specific to a particular emergency. Universal sizes make it more probable that a suit of acceptable fit is available during emergency egress, allowing for more efficient dissemination and successful fit.

However, the greatest advantage of a universal size is also its greatest disadvantage. Manufacturers use anthropometric data from samples of populations to establish suit sizing. For the consumer, size range information is generally represented by stature and/or mass figures. This method fails to communicate diversity of body morphologies across a population, as reiterated by the popular adage regarding immersion suits: *"one size fits none"*. One would, and should assume that they are able to correctly fit into an immersion suit if their stature and mass fall within the specified sizing range established by a manufacturer. Variability of anthropometrics across a similarly sized population may result in loose fitting seals, poor mobility, restricted respiration and impeded vision, reducing functionality and safety. In addition, post-abandonment thermal protective properties are reduced by water ingress and additional water weight reduces buoyancy, impeding an individual's ability to manoeuvre and stay afloat.

Individuals with body morphologies at the lower end of an immersion suit size range tend to be too small to properly fit within a suit. Due to their relatively smaller statures in comparison to the suit size, excess material creates folding and bunching in the chest and waist regions (Reilly, Kozey & Brooks, 2005). Accumulations of surplus material was shown to interfere with the zipping process, impede proper head location within the immersion suit hood, prevent adequate seals from being formed around the face and compromised overall mobility, hand function, respiration and vision.

Experimental observations suggest that individuals with mass and stature figures located in the mid-to-upper range of immersion suit sizing specifications achieve best fit and functionality. Despite having stature and mass values greater than a particular size specification, individuals who lay in the lower range of a suit size may benefit from using a smaller suit. Reducing excess suit material can have several advantages: increase of overall mobility and functionality, facilitation of faster donning through use of a smaller, more manageable suit and the creation of tighter neck and wrist seals. It must also be stressed that a suit which is too small for an individual has disadvantages that can be as detrimental as an oversized suit. If a body and its extremities are too large to fit within a suit zipper closure may be impeded, wrist and neck seal may be restrictive and overall mobility and comfort can be compromised. It is imperative that the individual who intends to use a particular suit not only try it on for size, but also perform functional tests prior to purchase or departure for a marine environment (Leese & Norman, 1979).

4.2 *Carry Bags & Additional Contents*

Immersion suits should be stowed in their accompanying carry bag until needed. Carry bags provide several benefits, most notably suit protection, organized stowage, convenient transportation and the ability to combine several types of survival equipment into one package. A suit stowed without a carry bag is functionally less diverse then a suit stowed in a carry bag. In an emergency, immersion suits may have to be transported to a muster area or alternative safe zone prior to donning. An unpacked suit can impede user speed and mobility in escape procedures and increase chances for suit damage due to exposure to the surrounding environment.

Some carry bag models are comparatively spacious and study observations revealed that this allows for easier removal of the suit from the bag. Although larger bags allow for easier suit extraction, extra space within a carry bag can be used to stow additional equipment which may be helpful during emergency egress; turning a standard immersion suit and carry bag into a more comprehensive survival package. Examples of small, light additional equipment include clothing, visual aids and tools. Easy to stow, useful clothing include heavy, loose fitting socks, insulated pants, shirts, caps and gloves. Apart from clothing, watertight flashlights, multi-tools, small first aid kits or disposable glow sticks can be valuable additions to carry bag contents. Glow sticks can aid vision during suit donning and abandonment, while also provide a supplementary light source for survivors and searchers to locate each other. Special precaution and protective measures should be taken to ensure that potentially corrosive chemicals that can damage immersion suits, including batteries and glow sticks are adequately sealed and quarantined in case of accidental discharge. Duct tape can help seal an immersion suit, while also a versatile tool which may be useful for a variety of purposes. Brooks et al. (2001) note that duct tape is often brought to sea and used at muster stations for the purpose of shutting loose seals (i.e. wrist seals) in order to maximize the watertight integrity of an immersion suit.

These are only a sample of useful, light, compact and economical equipment which can be stowed and transported within a carry bag to create a more comprehensive personal survival system. Although these items may not have the ability or need to be used during an emergency, their presence could be instrumental in contributing to successful abandonment, survival and rescue.

4.3 *Personal Vulnerability During Initial Donning Procedures*

Donning an immersion suit in benign, stable conditions can be a difficult procedure for many individuals. However, being forced to don an immersion suit in a marine emergency can prove to be both more physically and psychologically challenging. Initial gross movements needed for donning include removing footwear (if necessary - immersion suit models vary), unpacking the carry bag, unfolding the suit and entering the extremities within its confines. These movements can lead to loss of balance and increase the possibility of slips, trips and falls. An unprotected body may be exposed to wet, slippery, cold, crowded environments, laden with sharp objects or other hazards. Prior to, and during abandonment it is important if possible, to find a relatively unobstructed, dry and safe area to don an immersion suit.

It is recommended that users practice donning in various settings and try differing techniques and methods. Throughout the trials its was observed that participants employed a range of varying procedures during initial donning tasks, familiarizing themselves with what felt and worked best for them. For example, in certain motion rich environments it may be advantageous to sit on the floor to decrease ones centre of mass, lean against objects or take advantage of items in the surrounding environment for stability and support.

4.3.1 *Cardiovascular Demands*

Overall, the mean peak cardiac output recorded was 82.1% of participants' theoretical maximum heart rate, defined as "vigorous-intensity physical activity" by the Centers for Disease Control and Prevention (2011). Heart rate values ranged from a "moderate" 52.3% cardiac intensity to 100.0% of participants' predicted maximum heart rate. Donning an immersion suit is not extended physical activity, nor is it uniform in its physical demands or intensity. However, the rapid escalation of physical demand and stress placed on the cardiovascular and muscular systems during the initial gross-movements of donning procedures can be hazardous to health, especially for untrained individuals unaccustomed to intense physical exertion.

4.4 *Removable Liner*

Immersion suits are constructed of single or multiple layers of material. Single layer designs consist of waterproof fabric with thermal properties, while multi-layer suits generally have a waterproof outer shell, lined with an insulating layer. Brooks (2003) notes that the removable option is advantageous as it allows the ability to change liners based on specific cold water conditions, while also convenient for laundering. Experimental observations revealed that during the donning process liners using snap buttons as an attachment mechanism within the suit periodically interfered with participant donning and in extreme scenarios prevented successful donning completion.

Liner attachment buttons, particularly within suits' lower legs were shown to detach from the outer shell during the physically vigorous process of rapid suit unpacking and donning. This is concerning for two important reasons: first, the presence of loose, unbuttoned fabric increases the potential to cause tangling and obstruction within the legs or arms; second, should an individual successfully don a suit with a detached liner, the shifting fabric within the extremities could leave part of the body without thermal coverage. In this event, a thin waterproof layer may be the only barrier between the skin and water, increasing the rate of total body heat loss.

4.5 *Lifting Harness*

Immersion suit lifting harnesses are a component offered by manufacturers (whether optional or standard) designed to aid in the retrieval of an individual from water (see Figure 2). Observations revealed that rapid donning dislodged this particular harness system, consequently interfering and in extreme cases prohibiting donning completion. If a harness is dislodged from its intended stowage position after successful donning completion the material presents a tangle hazard and can compromise user retrieval via the system. Although the addition of a lifting harness on an immersion suit can aid in the rescue process, design and location of the component can have negative impacts upon donning.

Figure 2. A properly configured lift harness system post-donning

4.5.1 *Detrimental Effects of Lifting Harness: Two Case Studies*

During the trials two issues regarding the lifting harness commonly occurred throughout donning procedures. The first scenario saw the lifting harness unintentionally released from its Velcro straps located on the chest leaving the harness dangling from the suit. The second scenario saw the harness which is intended to be looped between the legs, dislodged from its stowage position during donning and end up at the side of an individual's body once donned. Both unintended harness positions can create tangle hazards during egress and may render the system inoperable. The two scenarios described above regularly occurred across participant donning trials, but generally did not interfere with the success of task completion. However, two specific cases were observed during the experimental trials where the lifting harness played a direct role in prolonging or entirely preventing completion of suit donning.

In the first case, a participant donning his suit in a darkened, motion rich environment (Condition 6) became entangled in the lifting harness when he accidently dislodged it in the initial donning stages. After repeated failed attempts in getting his arms into the suit, he eventually realized that he was tangled in the lifting harness on the posterior side of his body. Upon discovering this, the participant unhooked the harness buckle and wriggled free. The remainder of the tasks were then successfully completed, while the inoperable lifting harness hung from the suit around his lower extremities.

The second participant encountered similar lifting harness trouble while donning his suit in the same darkened, motion rich condition (Condition 6). However, in this scenario the participant did not realize the dislodged and dangling lifting harness was preventing his upper limbs from entering the suit. Comparable to case one, the participant successfully unpacked and got his lower body within the suit. However, during this process the lifting harness was unintentionally released from its stowage position on the chest and became entangled behind him and within the now half-donned immersion suit. This restricted his trunk and shoulders from fitting into the top-half of the suit, subsequently restricting his arms from fitting into the sleeves. After over three minutes of struggling and many repeated attempts, the participant failed to get his arms within the suit sleeves, don the hood or seal the zipper and gave up disorientated, exhausted and frustrated.

Although this particular design of lifting harness routinely became dislodged, it rarely created problems during donning. However, as described, the potential for this particular loose fitting lifting harness design to have a drastically negative impact is present. Further study into lifting harness configurations and their performance in rapid immersion suit unpacking and donning is necessary to provide an effective device which eliminates the possibility of impeding donning tasks. Users need to be aware of how a lifting harness can hinder donning, as well as how to identify and mitigate such issues if and when they arise.

4.6 *Zipper*

The anterior zipper of an immersion suit is a critical and fragile component of the suit system, long cited as a major concern due to its vulnerability to corrosion and physical damage (Brooks, 2003). Even while using brand new suits with lubricated zippers in perfect working order, participants encountered issues which both increased donning times and decreased levels of reported user confidence and comfort.

Experimental observations revealed that a major factor in preventing optimal zipper function is the presence of excess, loose suit material creating bunching around the trunk of the body; a potential by-product of one-size fits all suits. Excess suit material bunching adds variability to zipper track positioning along the suit affecting zipper movement efficiency. Throughout the trials participants routinely commented about being nervous and hesitant when attempting to close the zipper, due to its seemingly unpredictable and erratic movement when force was applied, especially near the face and mouth region. This often led to participants not wanting to fully close the zipper, which in turn compromised the face seal and watertight integrity of the entire suit system. These findings support the rationale for an offset neck seal closure design. Moving the zipper track away from the chin and mouth to a less sensitive region of the body would combat user hesitation to fully close the zipper, as seen in central split neck seal design.

Heavy immersion suit zippers move easier and with less force when the suit material and zipper tracks are flat. Additionally, even new, lubricated zippers may still have a tendency to stick during closure. Zipper closure can be facilitated by holding the bottom portion of the track and applying force downwards with one hand, while the opposing hand pulls the zipper towards the head. This keeps the zipper track as straight and flat as possible allowing for the smoothest movement and efficiency of force transfer.

4.7 *Wrist Cuffs*

Immersion suit wrist cuffs must be tight enough to prevent water leakage into the suit, yet loose enough to accommodate a range of hand and wrist sizes while maintaining hand function and comfort. A variety of materials may be used for immersion suit wrist cuffs, though both suits used in the experiment had cuffs constructed exclusively of rubber. All thirty-two participants were able to get their hands through the wrist seals and adequately position the cuffs. Observations indicated that for a given suit size, individuals on the lower end of a size range fit their hands through cuffs easier and with less effort than individuals of larger stature and mass, suggesting that the wrist cuffs may not have established a completely watertight seal. Although this hypothesis was not tested in the experiment the use of duct tape for sealing wrist cuffs suggested by Brooks et al. (2001) would introduce a safeguard against potentially ill-fitting seals.

Wrist cuff design also affects how hand protection secures against the wrist and lower forearm of a suit. In comparing the two suits, notable differences appeared which affected hand protection and function. The immersion suit on the left of Figure 3 shows a flat, unobstructed cuff design. This allows the hand protection to slip over and lay on top of the wrist cuff material flush and with little hindrance. In contrast, the immersion suit on the right of Figure 3 reveals a wrist cuff design where excess, loose material from the sleeve creates bunching, which in turn obstructs the wrist cuff. The bunching of excess material over the wrist cuff can be attributed to the sleeve design and a larger suit size range, creating excess material in comparison to the individuals' morphology. Excess sleeve material can impede hand protection donning and placement on the hand and forearm. Additionally, once donned excess sleeve material can place force on the base of the glove, sliding it out of its intended position.

Figure 3. Comparison of two popular designs of wrist cuffs & hand protection stowage compartments

4.8 *Hand Protection*

An inverse relationship exists between bulky hand protection construction and user hand performance in cold environments. Without physical protection, exposed hands cool relatively quickly and thus, lose dexterity, grip strength and function (Bensel & Lockhart, 1974; Geng, Kuklane & Holmér, 1997). In contrast, implementing hand protection in the form of various glove or mitten configurations (Note: for the convenience of shorthand this article uses the terms "hand protection" and "gloves" interchangeably to refer to all designs and configurations of hand protection) will provide physical and thermal protection, but reduce hand mobility and dexterity due to the presence of obstructive material around the fingers and hands.

The ultimate goal of immersion suit hand protection is to provide adequate fit and function for users' hands while maximizing thermal properties. However, historic and contemporary commercial hand protection fails to fully optimize these requirements, while the degradation of manual function continues to be of concern. Current hand protection has trade-offs and users must judge accordingly under the specific circumstances when, and if hand protection should be implemented. Marine abandonment immersion suits offer various configurations and designs of hand protection. The current discussion will not focus on specific hand protection sizing, materials, designs (i.e. mitten vs. index finger free vs. five finger hand protection) or between integrated and detached hand protection configurations. These issues deserve their own detailed analysis and discussion outside the scope of this research. The immersion suits used in the experiment both had detached hand protection configurations. Discussion here within will focus on the user interaction and performance of the systems during hand protection unpacking, donning and functionality.

4.8.1 *Detached Hand Protection Stowage & Release*

Brooks (2008) suggests that hand protection is best provided as a separate item stowed on the sleeve rather than incorporated into the suit itself. The rationale being that it allows hands to be unimpeded and free to carry out tasks which may otherwise be hindered by the presence of bulky gloves. Hand protection which is not integrated into a suit are generally stowed in pouches on the suits forearm and attached by a tether to prevent loss. There are various stowage pouch configurations but generally have a comparatively (1) open, unimpeded or (2) secure, protected stowage design (see Figure 3).

A more open, unimpeded design allows for quicker and easier deployment but may promote hand protection release at unwanted times, especially during the vigorous motions of carry bag unpacking and initial suit donning procedures. While this eliminates the need for an individual to extract hand protection from stowage pouches, a dangling glove can get caught in surrounding obstructions, tear the tether and damage the suit. Several instances occurred where released tethered hand protection became caught inside the suit and prevented the anterior zipper from being closed. Additionally, a released glove can spin freely and entangle with itself or with the other hand protection when released. A more secure, protected design ensures that hand protection release requires intentional and specific actions by the user. The suit used in the experiment features a flap of material sealed by Velcro and a single snap button which firmly stows the tethered glove. Although this more protected design keeps the hand protection stowed and out of the way until desired, its reduced accessibility can inhibit the glove from being released.

Hand protection should only be released from stowage pouches after initial donning and zipper sealing and immediately prior to when the user intends to don them. This maximizes bare hand function for completing critical tasks and minimizes the probability of hand protection tangling and damage once released. Both gloves should be released prior to any hand protection donning. If not, the opposing hand now covered by a glove may prevent successful release of the opposing hand protection from its stowage pouch due to reduced manual dexterity and function.

4.8.2 *Detached Hand Protection Donning*

Once hand protection is released from the stowage pouches the process of entering hands into the gloves can commence. Observations suggest that the initial task of fitting hands into gloves subjects a large amount of stress and uneven pulling on hand protection, contributing to suit damage. Pulling from the base of a glove requires an individual to grip the material by the thumb and finger(s) to exert force. Even a small reduction in hand/finger strength or the addition of a wet and/or cold environment may prevent this from being successfully achieved.

When donning the first glove, one is able to use the opposite, bare hand to secure and position the hand protection, allowing unfettered hand and finger function throughout the process. However, when donning the second glove, the opposing hand is covered by the recently donned hand protection. This results in a more difficult procedure due to the now reduced manual function of a gloved hand. Poor fit, reduced hand function and compromised physical and thermal protection are by-products of having to don a second glove; an unavoidable task in detached hand protection donning.

4.8.3 *Detached Hand Protection Wrist Straps*

Wrist straps are intended to tighten and secure hand protection against immersion suit cuffs. This provides the only defence against water ingress into the glove and thermal protection for the hand. Additionally, they act as a secondary barrier of protection from water ingress into the suit by way of the wrist seals. This procedure must be completed with either one or two hands covered by hand protection, depending on the order in which tasks are performed. Due to the fine, accurate movements needed to accomplish the task, high hand dexterity and unobstructed vision are advantageous.

The wrist straps of the suits used in the experiment had several design deficiencies which either prevented participants from attaching the system correctly, or in some cases, if successfully attached, failed to provide a functional additional seal around the wrist. It was observed that even in well-lit conditions participants had difficulty distinguishing between the wrist strap material and the male-female Velcro attachments. A contributing factor was the low contrast between the wrist strap, wrist cuff, hand protection and Velcro attachment points, all being black. Low visual contrast combined with poor manual function and somatosensory information forced participants to estimate where the Velcro strap attachment point locations were, contributing to high task error rates. One participant, after several failed attempts, rubbed both sides of the strap against her exposed face in order to feel which side was rough Velcro, and thus which was the correct way to circle the strap around the wrist for attachment.

In addition to donning issues, the actual usefulness of the wrist straps was questioned by some participants. While wrist straps themselves were of adequate length to fit all participants’ wrists, Velcro attachments relative to wrist size were not always in ideal positions to achieve a tight seal, especially those with smaller wrist circumferences. A wrist strap which fails to provide a tight seal around the glove and wrist fails to serve any purpose.

4.8.4 *Hand Protection Stowage Pouch Design Flaw: A Case Study*

It was revealed that the suit with the more secure hand protection stowage system has a crucial design flaw which was shown to inhibit hand protection donning due to inadvertent male-female Velcro being able to connect. The flap adorned with Velcro intended to seal the stowage pouch shut can inadvertently impede entrance of the hand into the glove when hand protection is deployed. Once deployed, the Velcro on the stowage pouch flap can attach to the Velcro on the glove, intended for the wrist strap, thus blocking the hand protection entrance at its base (see Figure 4). Several similar instances during the trial revealed that once the inadvertent attachment of unintended male-female Velcro pieces occurred, participants had difficulties in both identifying and remedying the problem that was preventing hand entry into the glove.

Figure 4. Design flaw: Inadvertent blocking of entrance into hand protection

4.8.5 *Improving Hand Protection Design to Facilitate Functionality*

Numerous factors must be assessed in order to optimize immersion suit hand protection design; a reinvention of the traditional system is needed. Increased emphasis on research and development in this area is necessary to address a number of underlying design issues related to immersion suit hand protection in abandonment and survival. However, over the course of experimentation through observation and discussion with participants several simple, cost-effective design modifications were proposed for current detached hand protection system improvements:

- The addition of an external pull tab(s) around the base of a glove would facilitate hand protection donning and the ability to adequately fit hands. This would serve two main purposes: (1) more effectively utilize muscular strength of larger muscles, relying less on fine finger strength and dexterity and (2) reduce direct stress placed on hand protection itself, reducing wear and damage.
- Increasing hand protection surface friction on the palm and fingers would contribute to improved user grip and control in donning and execution of post-donning tasks requiring manual operation. This is especially valuable in cold and/or wet environments.
- High suit colour contrast would help users differentiate between components. This is true not only for the hand protection and wrist strap system, but also other immersion suit components to facilitate easier, quicker donning with less hesitation and number of errors.
- The wrist strap concept needs to be designed to better facilitate easy attachment. This could be achieved through a clasp-like addition to the system which maintains position and restricts strap movement, guiding the attachment process.
- Increasing the size (both length and width) of Velcro attachments on each part of the wrist strap system would ensure that regardless of wrist circumference users are able to adequately secure the straps to maximize watertight integrity.

4.9 *Face Shield*

Over one third of the entire human body's resting metabolic heat production is lost from the face, while over one half is lost from the head as a whole (Golden & Tipton, 2002). The immersion suits used in the experiment were equipped with face shields which, when donned are intended to cover the chin, mouth, mid-to-lower cheeks and lower nose, leaving the forehead and eye region exposed (which varies slightly depending on individual physical characteristics).

4.9.1 *Face Shield Stowage, Deployment & Attachment*

Both suits use a similar face shield stowage configuration: the face shield flap folds back and attaches via Velcro to the posterior side the immersion suit hood. When released it spans horizontally across the face to attach to the opposing side of the hood via Velcro. It was revealed that this stowage design prevented participants from locating or successfully deploying the system. Alternatively, if the face shield is stowed detached it would provide easier access during donning procedures. Although this makes locating the system easier by eliminating the detachment task, the free and loose face shield can impede hood donning, zipper sealing and other tasks. Additionally, if subjected to windy conditions or violent motions, a flapping face shield can obstruct vision and pose a safety risk to the eyes.

Deployment of the face shield is generally the last task to perform in the suit donning process. At this point, the majority of users will have donned hand protection and with their now reduced manual function may struggle to feel the face shield in its stowage location. Some participants chose to release and don the face shield prior to hand protection donning to take advantage of bare hands. This usually resulted in higher levels of task success, however, in many of these instances participants quickly complained of two issues: (1) obstructed vision, some being completely blinded by the face shield once attached across the face, and (2) increased respiratory difficulty due to the physical barrier over the mouth and nostrils (see Figure 5). This reduced efficiency of air exchange and obstructed vision, posing risk for subsequent donning tasks or abandonment procedures. During the experimental trials after participants attached the face shield many immediately detached it due to feeling uncomfortable and claustrophobic.

Some participants were unable to attach the face shield because the system was too short to span across the face. Physical head size, orientation and positioning within the hood may influence whether face shields can be successfully attached and if so, what position it lies in across the face.

Figure 5. Comparison of Velcro male-female face shield attachment sites across the face

5 CONCLUSIONS

Marine abandonment immersion suits are vital safety equipment which can dramatically increase chances of survival for individuals exposed to harsh environments. However, there are opportunities to improve current immersion suit systems to reduce equipment donning challenges users face. There are inherent design problems in immersion suit components and construction which transfer negatively and impact upon donning and survival procedures. It is inadequate to simply have a well maintained and properly fitted suit. Survival in an emergency at sea depends on the ability for individuals to be able to successfully identify and negotiate problems. A high level of immersion suit proficiency is only achieved through practice and interaction with the specific suit system intended to be used in an emergency. Familiarity of one's immersion suit is imperative in order to recognize how to maximize a suit's effectiveness, while avoiding or mitigating any detrimental effects in its design or functionality.

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